Growth and characterisation of InAs/InGaSb/InAs/AlSb infrared laser structures

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The authors have studied the molecular-beam epitaxial growth of type-II heterostructures for mid-wavelength infrared lasers. Based on their photoluminescence spectra and X-ray diffraction patterns, it is found that the quality of these heterostructures is highly sensitive to the growth temperature and the interfacial bond type.

As a result of growing military and commercial demand, there is considerable research in mid-wavelength (3–5μm) and long-wavelength (8–12μm) diode lasers aimed for high output power and non-cryogenic operation [1]. The precise control over layer thickness provided by molecular beam epitaxy (MBE) has allowed the creation of novel lasing materials, new lasing transitions, and record-setting performance. For example, a unipolar quantum cascade (QC) laser has been demonstrated [2] using MBE-grown AlInAs/GaInAs heterostructures and band-structure engineering. Furthermore, it has been predicted theoretically [3, 4] and demonstrated experimentally [5, 6] that infrared (IR) QC lasers based on the InAs-GaSb-AlSb family can provide better efficiency because of the type-II alignment between InAs and GaSb.

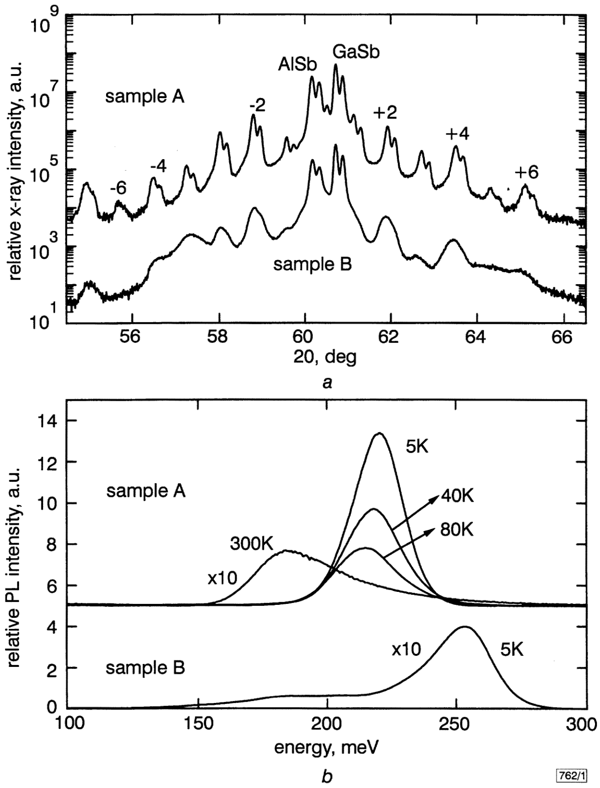

Fig. 1 *Single crystal x-ray diffraction scans and photoluminescence spectra at different temperatures for sample A (superlattices grown at 400°C) and sample B (superlattices grown at 450°C)*

a Single crystal x-ray diffraction scans
b Photoluminescence spectra

In this Letter, we report the growth and investigation of *n*-ML InAs/10-ML $In_xGa_{1-x}Sb$/*n*-ML InAs/14-ML AlSb, with $5 \leq n \leq 8$. This particular structure, used as a basic unit for a variety of type-II laser devices [5, 6], has been grown at different temperatures and with different interfacial bonds. Samples are grown on (001) GaSb substrates in a Riber MBE chamber equipped with a valved As cracker and an EPI-175 cracked Sb source. The growth temperature sensor is calibrated by the RHEED phase transition of GaSb. We assume that the 1×5 to 1×3 RHEED phase transition of GaSb occurs at 380°C under 1.5 ML/s Sb_2 flux [7], where the Sb cracker zone temperature is kept at 800°C. All samples consist of a buffer layer of 0.3μm GaSb (grown at 500°C) followed by 1μm AlSb (grown at 550°C), a 20- to 35-period superlattice, and a capping layer of 0.2μm AlSb followed by 100Å GaSb (both grown at 450°C). Layer thicknesses are calibrated by RHEED oscillations and x-ray diffraction.

Commonly, InAs/InGaSb/AlSb laser structures are grown at 440°C [5, 6] as a compromise between the usual growth temperatures for InAs, InGaSb, and AlSb. In this work, we find that a growth temperature of 450°C introduces significant interlayer mixing between InAs and InGaSb which degrades radiative efficiency and reduces emission wavelength. We find significantly better results at 400°C. Similarly, InAs/InGaSb detector structures have been found to grow best at temperatures < 400°C but the cause of the degradation at higher growth temperatures in these structures is not known [8]. Different interface bonding between layers is possible when the adjacent materials have neither common cations nor anions. For instance, either InSb-like or GaAs (or AlAs)-like interfacial bonds can be formed between InAs and GaSb (or AlSb) depending on the growth sequence.

All growth parameters are the same for samples A and B except for the growth temperature (400°C for sample A against 450°C for sample B) and all growth parameters for samples C and D are the same except the interfacial bond type (InSb-like for C against GaAs and AlAs-like for D).

Photoluminescence (PL) spectra are obtained with a BOMEM DA3.02 Fourier transform infrared spectrometer with a KBr beam-splitter. Samples are mounted on a Janis Supertran cryogenic dewar with CaF_2 windows on the emission port and excited with an SDL-2360 laser diode with an output wavelength at 810nm and an excitation intensity of 10W/cm². The large room-temperature blackbody radiation peak has been eliminated by a double-modulation technique. The bias of the pumping diode is sinusoidally modulated at 45kHz. The PL signal is detected by a HgCdTe 14μm photoconductor at 77K with a wedged semi-insulating GaAs filter to eliminate stray pump light. The detected signal is demodulated by a commercial wide IR bandwidth, low frequency AM receiver prior to the Fourier transform electronics.

Fig. 1*a* displays the single crystal x-ray diffraction scans from samples A and B, both 35-period superlattices with $n = 8$ and $x = 0.28$. For sample A, the Cu-K_α doublets are well resolved and up to the seventh-order satellite peak can be observed. The fact that the satellite peaks for sample B occur at the same place as for sample A indicates that these two samples have an identical average lattice constant and thickness for each period. However, the Cu-K_α doublets are not resolved and the intensity is weaker for sample B, implying a superior material quality and sharper interfaces for the superlattice grown at 400°C as opposed to that grown at 450°C.

Fig. 1*b* shows the PL spectra from samples A and B. Over the temperature range from 300 to 5K, the PL integrated intensity for sample A is approximately one order of magnitude stronger than that for sample B at the same temperature. For sample A, the PL peaks at 183meV at RT. When the temperature is decreased, the PL intensity increases and the PL peak shifts monotonically to a higher energy. A semi-log plot of PL intensity indicates a thermal tail when $T \geq 80$K. Below 80K, the PL linewidth is dominated by the inhomogeneous broadening probably due to interface roughness. At 5K, the PL intensity is 15 times stronger than that at RT and peaks at 220meV. The PL spectrum for sample B displays a single peak with an extremely slow turn-on. The main peak is at 252meV, which is 32meV higher than that for sample A grown at 400°C [Note 1]. A simple estimation using the four-band $k \cdot p$ calculation shows that one monolayer variation in the InAs well thickness can cause a 38meV change in optical bandgap. These findings suggest that when the growth temperature of the superlattices is 450°C, layer intermixing at interfaces takes place, which results in a rougher interface, lower emitting efficiency, and a higher emission energy.

The influence of different interfacial bond characteristics on carrier concentration and bandgap of detector structures has been reported [9, 10]. However, the influence on laser structures (especially regarding the radiative efficiency) has not been addressed. Fig. 2*a* shows x-ray scans from samples C and D with $n = 6$, $x = 0.3$ and a 20-period superlattice grown at 400°C. Owing to a smaller number of periods for sample C, the K_α doublets are not well resolved as for

Note 1: This observation is consistent with the data presented in [4]. For example, the 88 K PL peaks at 300meV for a 21Å-31Å-21Å-43Å structure grown at 440°C in [4] as compared to 243meV for the same structure grown at 400°C here.

sample A. However, the contrast between these two curves in Fig. 2*a* is clear; the sample with InSb-bonds has sharper interfaces. Note that the Bragg angles of the satellites are different for samples C and D. This reflects the difference in average lattice constants of the structures due to the different interfacial bonds. In addition, as shown in Fig. 2*b*, sample C has a narrower PL linewidth and an approximately 10 times stronger PL intensity than sample D. These observations indicate that superlattices grown with InSb-like bonds have better interface quality [Note 2] and more efficient luminescence, both of which are extremely important laser characteristics.

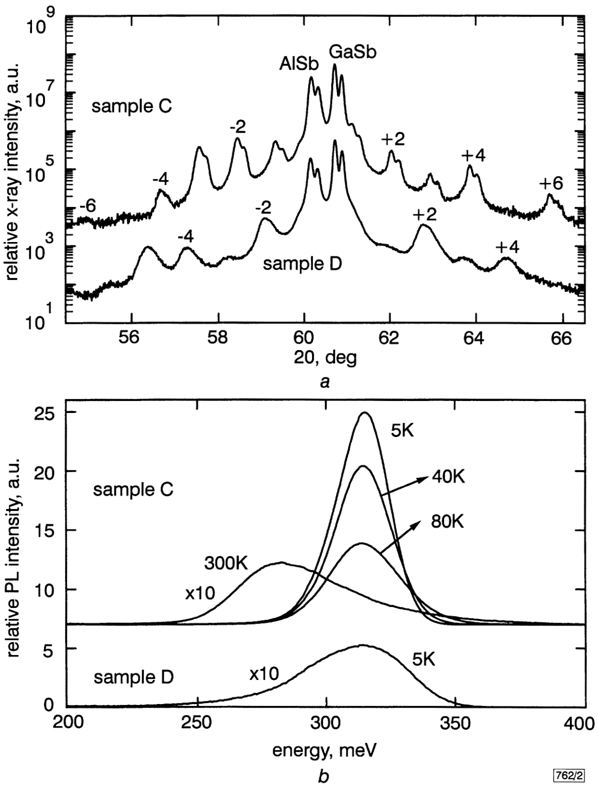

Fig. 2 *Single crystal x-ray diffraction scans and photoluminescence spectra at different temperatures for sample C* (*with InSb-like interfacial bonds*) *and sample D* (*with GaAs- and AlAs-like interfacial bonds*)

a Single crystal x-ray diffraction scans
b Photoluminescence spectra

Note 2: Owing to the small lattice constant of GaAs, the 0th order satellite peak of sample D coincides with the GaSb one. This indicates a 0.7% lattice mismatch between the superlattice and the AlSb cladding layer. A study with GaAs-bonded superlattices cladded with lattice matched GaSb is underway.

In conclusion, we have investigated the MBE growth of type-II infrared laser structures and characterised the samples by RHEED, x-ray diffraction, and PL. We find that two important laser parameters, the effective bandgap and the radiative efficiency, are very sensitive to the growth temperature and the interfacial bonds. Our data suggest that interdiffusion between InAs and InGaSb layers, which degrades the interface sharpness and sample quality, is responsible for a poorer radiative efficiency and higher energy gap for superlattices grown at 450°C. Furthermore, we have shown that it is important to control the interfacial bonds: the sample with InSb bonds shows a PL at least one order of magnitude more efficient than that with GaAs and AlAs interfacial bonds.

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